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TECHNICAL MEMORANDUM No. CAL-27

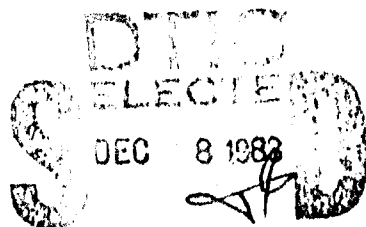
VALVELESS PULSE JET INVESTIGATIONS

PART I

TESTS OF SMALL SCALE MODELS

By

JOSEPH G. LOGAN, JR.



MAY 1949

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ERRATA

for

Squid Technical Memorandum CAL-27 entitled, "Valveless Pulse
Jet Investigations, Part I, Tests of Small Scale Models" by
Joseph G. Logan, Jr. dated May 1949

- Page 8 - s 13 and 15 - should read square inch gage instead of
square in gage
- Page 13 - Reference (2) - should read Project Squid Annual Program
Report, (Description of pressure gage developed by
New York University) p. 17, January 1, 1948
- Figure 5,
Page 20 - should read "Variation of Specific Impulse with Tailpipe
Length for 3.0 inch Diameter Combustion Chamber" instead of
"Variation of Specific Impulse with Tailpipe Length"
- Figure 6,
Page 21 - should read "Variation of Specific Impulse with Tailpipe
Length for 3.50 inch Diameter Combustion Chamber" instead of
"Variation of Specific Impulse with Tailpipe Length"

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SQUID TECHNICAL MEMORANDUM No. CAL-27

VALVELESS PULSE JET INVESTIGATIONS PART I TEST OF SMALL SCALE MODELS



By

JOSEPH G. LOGAN, JR.

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MAY 1949

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SUMMARY

The results of an investigation of small valveless intermittent engines are described. These experiments were undertaken to determine if thrust and specific impulse values were appreciably affected by changes in fuel, methods of fuel injection and duct geometry.

The tests appear to confirm the expectation that high specific impulse values are obtainable with valveless engines. Mean values of approximately 2200 seconds were obtained in the tests. The experiments indicate, also, that an optimum configuration exists for each particular fuel and method of fuel injection.

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INTRODUCTION

Preliminary experiments conducted with valveless intermittent engines were reported in Reference 1. Further analysis, based upon a number of assumptions whose validity remains to be verified, revealed that the valveless pulse jet, even aside from its obvious advantage of simplicity, is potentially a more efficient power plant than either the pulse jet or ram jet, at least for certain specific applications. One of the most interesting of the applications consists of using a valveless pulse jet as a power plant for the jet-propelled helicopter. It appears that the valveless pulse jet will in this connection, have the following advantages over a conventional pulse jet engine:

1. Greater simplicity
2. Longer operating life
3. Greater flexibility of operation
4. Considerably better fuel economy

It also appears that the valveless pulse jet will possess one major advantage over the conventional ram-jet engine: considerably better fuel economy within the conventional helicopter rotor top speed range of 400 to 600 feet per second.

The mean pressures obtained as the result of an intermittent burning process in a partially opened tube are influenced by fuel characteristics and methods of fuel injection. Since the wave motion in these engines is established as a result of the intermittent combustion, it is to be expected that fuel characteristics as well as methods of fuel injection will also influence the optimum tube design.

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If it is possible to determine a tube design yielding the maximum effects of these waves, such a tube should yield much higher values of specific impulse than are obtained at the present time. Engines depending upon such wave effects should prove to be sensitive to changes in overall configuration. An optimum tube design should exist for a given set of operating conditions and a change in any single condition should then require a change in overall configuration to obtain optimum thrust and specific impulse values.

At the present time it is not possible to predict by theoretical methods the influence of the several operating variables upon overall jet operation. This memorandum describes the initial series of experiments conducted with small valveless engines to determine:

1. To what extent thrust and specific impulse values are appreciably affected by small changes in overall configuration
2. If an optimum tube configuration exists for a given set of operating conditions
3. Whether changes in fuel characteristics and methods of fuel injection require corresponding changes in duct configuration for maximum thrust and specific impulse values.
4. If high specific impulse values can be obtained with engines of this type as a result of variations in overall configuration.

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EXPLORATORY EXPERIMENTS

Exploratory experiments were first undertaken to determine if changes in fuel, methods of fuel injection and duct configuration produced the expected large variations in thrust and specific impulse.

An experimental valveless engine was constructed having a combustion chamber 3 inches in diameter and a tailpipe 1.5 inches in diameter (Fig. 1). This tailpipe, with a straight exit, was varied in length from 16 to 22 inches. In order to determine the effect of different methods of fuel injection, two systems were utilized. The air and fuel were premixed and injected through the same inlet, or injected separately, without premixing. In the exploratory series, tests were conducted with propane and gasoline.

The model was mounted on the small thrust stand shown in Fig. 2. Thrust readings were obtained with a small spring balance. In all tests, corrections were made for the thrust contributed by the continuous air supply. Propane consumption was determined with a standard rotameter. At the time these tests were conducted, a small rotameter was not available for the determination of gasoline consumption. Fuel flow was determined by timing the rate of consumption in a calibrated glass tube. In later tests, in order to observe the effects of a different type of hydrocarbon fuel, methane was used.

Table 1, Appendix A, shows the effect of changes in fuel, fuel injection methods and tailpipe length upon thrust and specific impulse. It may be observed that marked changes in specific impulse values occur as a result of changes in any one of these parameters. For these configurations maximum specific impulse values were obtained with separate air and fuel injection.

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Various types of exit configurations were tested (Fig. 1) to determine if similar marked changes in specific impulse occurred. In these tests combustion chamber diameters of 3.0 and 3.5 inches were used. Typical results of these measurements are shown in Table 2. With one combination, using a slightly flared exit, a mean specific impulse value of 2150 pounds thrust per pounds fuel per second was obtained. This value was obtained with a combustion chamber diameter of 3.5 inches. The sensitivity of the jet to changes in overall configuration is demonstrated by the decrease in specific impulse values from 2150 to 1300 seconds when the diameter of the jet combustion chamber was reduced to 3.0 inches.

In order to compare the results of these tests with the specific impulse values obtained from a small pulse jet, tests were conducted with the dynajet, Table 3. In this jet the fuel, gasoline, was premixed with the air before entering the combustion chamber. Average specific impulse values of 1200 seconds were obtained. Attempts to operate this jet with propane were not successful.

The flapper valves were removed and replaced by a flat plate. Tests were conducted with propane and gasoline, Table 4. It may be observed that maximum specific impulse values were obtained using propane, with the air and fuel premixed. With the experimental model separate air and fuel injection, in all cases, yielded maximum specific impulse values.

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INFLUENCE OF TUBE GEOMETRY

The exploratory experiments indicated that large variations in specific impulse values could be obtained as a result of varying fuel, methods of fuel injection and tube geometry. Tests were then conducted to determine if an optimum configuration existed for a given fuel and method of fuel injection.

Models were constructed with combustion-chamber diameters varying from 2.5 to 4.0 inches. Propane was used with separate air and fuel injection. Tailpipe lengths were varied from 13 to 18 inches at intervals of $1/4$ inch.

Fig. 3 shows the variation of specific impulse with tailpipe length for various combustion-chamber diameters. For the configurations investigated, an optimum value appears to exist with a combustion-chamber diameter of 3.5 inches and a 16.0-inch tailpipe. However, it was possible to obtain high specific impulse values with other configurations.

For example, a specific impulse value of 1900 seconds was obtained with a combustion-chamber diameter of 2.5 inches and a relatively short tailpipe of 14 inches. It is interesting to note that resonance could not be achieved with this combustion-chamber diameter for tailpipe lengths between 14.5 and 15.25 inches.

It may be observed that for each combustion-chamber diameter a maximum value of specific impulse is obtained in the range of tailpipe lengths investigated.

The irregular nature of the specific impulse curves appears to be typical of this type of device and indicates extreme sensitivity to small

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changes in configuration. Changes in tailpipe length as small as 2 per cent produced changes in specific impulse values as large as 10 per cent.

To determine if a hydrocarbon fuel with different characteristics would act in a similar manner in these experimental models, tests were conducted with methane using combustion chambers 3.0 and 3.5 inches in diameter. Mean specific impulse values of over 2100 seconds were obtained with both combustion-chamber diameters (Fig. 4). These peak values did not occur at the same tailpipe length. At a tailpipe length of 16 inches, which yielded the peak value for the 3.5-inch-diameter combustion chamber, the difference in specific impulse values was approximately 13 per cent.

The specific impulse values obtained using propane and methane, with combustion-chamber diameters of 3.0 and 3.5 inches, are compared in Figs. 5 and 6, respectively. For both of these combustion chambers, methane yielded the largest mean specific impulse values. Although the results of tests using the 3.5-inch-diameter combustion chamber are similar, large differences in the behavior of the two hydrocarbons were observed with the 3.0-inch diameter combustion chamber. When methane was used, the specific impulse values increased as the tailpipe length was increased. With propane, the specific impulse values decreased. At a tailpipe length of 17.0 inches, methane yielded twice the specific impulse value obtained with propane.

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MEASUREMENTS OF MASS FLOW AND INLET AIR PRESSURE

To determine the thrust developed per pound of air per second, measurements of mass flow were made using a calibrated orifice plate. Measurements of total pressure were made at the combustion-chamber air inlet with a standard pitot tube.

In these tests a standard 3/8-inch pipe was used as an air inlet. With the flared 2.0-inch tailpipe, the inlet-exit ratio was 1/18. The variation of the air specific impulse (pound thrust per pound air per second) with air-fuel ratio is shown in Fig. 7. As is indicated, mixtures were much leaner than stoichiometric. For both propane and methane the maximum air specific impulse was obtained with air-fuel ratios (by weight) of 32 to 1.

For the configurations investigated, maximum specific impulse values were obtained with total inlet air pressures of 2.5 pound per square in gage. During these tests, total inlet air pressures varied from 1 to 6 pounds per square in gage.

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DETERMINATION OF JET FREQUENCY

In previous experiments¹ it was observed that two stable operating frequencies were obtainable for a given configuration as a result of variation in air-fuel ratio.

In order to determine the frequencies of operation and pressure variation in the combustion chamber, a combustion chamber 4 inches in diameter with a 16-inch tailpipe was modified and a FM condenser-type pressure gage² was mounted as shown in Fig. 10.

Measurements of frequency for this configuration indicated that at the lean limit the frequency of operation was 130 cycles per second. At mixtures near stoichiometric, the frequency of operation was 180 cycles. Curves of pressure variation for these frequencies are shown in Fig. 8. Fig. 8 indicates that the time of rise to peak pressure was approximately the same for both frequencies.

The difference in frequency was due to the difference in time required for "blowdown" from the two pressure levels. Since the peak pressures obtained were due only to change in fuel-air ratio, there may be a significant change in burning properties at the lean fuel-air ratios in this type of jet.

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SCHLIEREN OBSERVATION OF A TWO-DIMENSIONAL
MODEL OF THE VALVELESS JET

In order to study the fuel-injection process and the combustion phenomena, a two-dimensional rectangular model was constructed as shown in Fig. 11. The area ratios were based upon the ratios used for the experimental model with 3.0-inch-diameter combustion chamber (Fig. 9). Vicor glass was used for the transparent sidewalls.

High-speed motion pictures (4000 frames per second) indicated that an intermittent fuel-and air-injection process occurred. This may offer a partial explanation for the stability of an intermittent burning process. Various stages are shown in Fig. 12. The film speed was not great enough to yield details of the combustion phenomena.

With this rectangular jet, extreme starting difficulties occurred. When resonance was obtained, the resultant thrust values were small. The reason for this effect of the rectangular shape of the combustion chamber on the behavior of the valveless pulse jet has not yet been explained although it has been suggested by Dr. G. Marksteir of this Laboratory that the periodic shape distortion resulting from the flexibility of flat walls may affect the wave phenomena and, perhaps, the shape of the flame front.

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CONCLUSIONS

These experiments, although of an exploratory nature only, tend to confirm the assumption that relatively high values of specific impulse may be obtained with valveless engines. Although it is not believed that an optimum configuration was established in these tests, mean specific impulse values of approximately 2200 were obtained. For applications in which the inlet losses of mass and momentum may be reduced appreciably, the valveless pulse jet, at high subsonic Mach numbers, should yield values of specific impulse appreciably higher than those obtained with conventional pulse-jet or ram-jet engines at the present time. This engine, therefore, appears to be a very promising propulsion unit.

Tests indicate that the valveless intermittent engine is extremely sensitive to small changes in overall configuration and appear to confirm the belief that an optimum configuration exists for a given set of operating conditions.

The results of these tests appear to have a special significance with regard to investigations undertaken to determine the influence of any single parameter upon the thrust and specific impulse values. In order to determine if any significant increases in thrust and specific impulse are obtainable as a result of change in operating conditions, it would be necessary to conduct tests with numerous overall configurations.

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PLANS FOR FUTURE WORK

1. Similar experiments will be conducted with gasoline to investigate the effects of changes in jet configuration and methods of fuel injection.
2. The two-dimensional model will be modified to improve the pulsating combustion, and spark photography will be used to study combustion phenomena.

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REFERENCES

¹ Logan, J., and Finamore, O., Project Squid Technical Memorandum No.
CAL-20, April 28, 1948

² Project Squid Annual Program Report, January 1, 1948

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APPENDIX A

Table 1

Experimental Model^{*} - Combustion Chamber 3.0 Inches in Diameter, Straight Tailpipe

FUEL	TAILPIPE LENGTH IN.	THRUST LBS.	SPECIFIC IMPULSE LBS. THRUST/LBS FUEL PER SEC.
(a) air and fuel premixed			
gasoline	8	0.69	550
gasoline	16	.81	700
gasoline	19	.81	600
gasoline	22	.69	550
propane	8	1.0	850
(b) separate air and fuel injection			
propane	8	1.95	1100
propane	16	2.95	1550
propane	22	2.0	950

Table 2

Experimental Model - Fuel, Propane - Separate Air and Fuel Injection

TAILPIPE	THRUST LBS.	SPECIFIC IMPULSE LBS. THRUST/LB FUEL PER SEC.
(a) 3.5 inch diameter combustion chamber		
D	2.5	2150
E	2.76	1600
F	3.25	1350
(b) 3.0 inch diameter combustion chamber		
D	2.5	1300

Table 3

Dynajet with Flapper Valves - Fuel, gasoline - Air and Fuel Premixed

THRUST LBS.	SPECIFIC IMPULSE LBS. THRUST/LBS FUEL PER SEC.
2.75	1200

^{*}In all tests fuel pressures varied between 4 and 12 lbs.

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Table 4

Dynajet - Flapper Valves Replaced by a Flat Plate

FUEL	THRUST LBS.	SPECIFIC IMPULSE LBS. THRUST/LB FUEL PER SEC.
(a) air and fuel premixed		
gasoline	1.05	1100
propane	1.75	1250
(b) separate air and fuel injection		
propane	1.25	950

EXPERIMENTAL MODELS INVESTIGATED

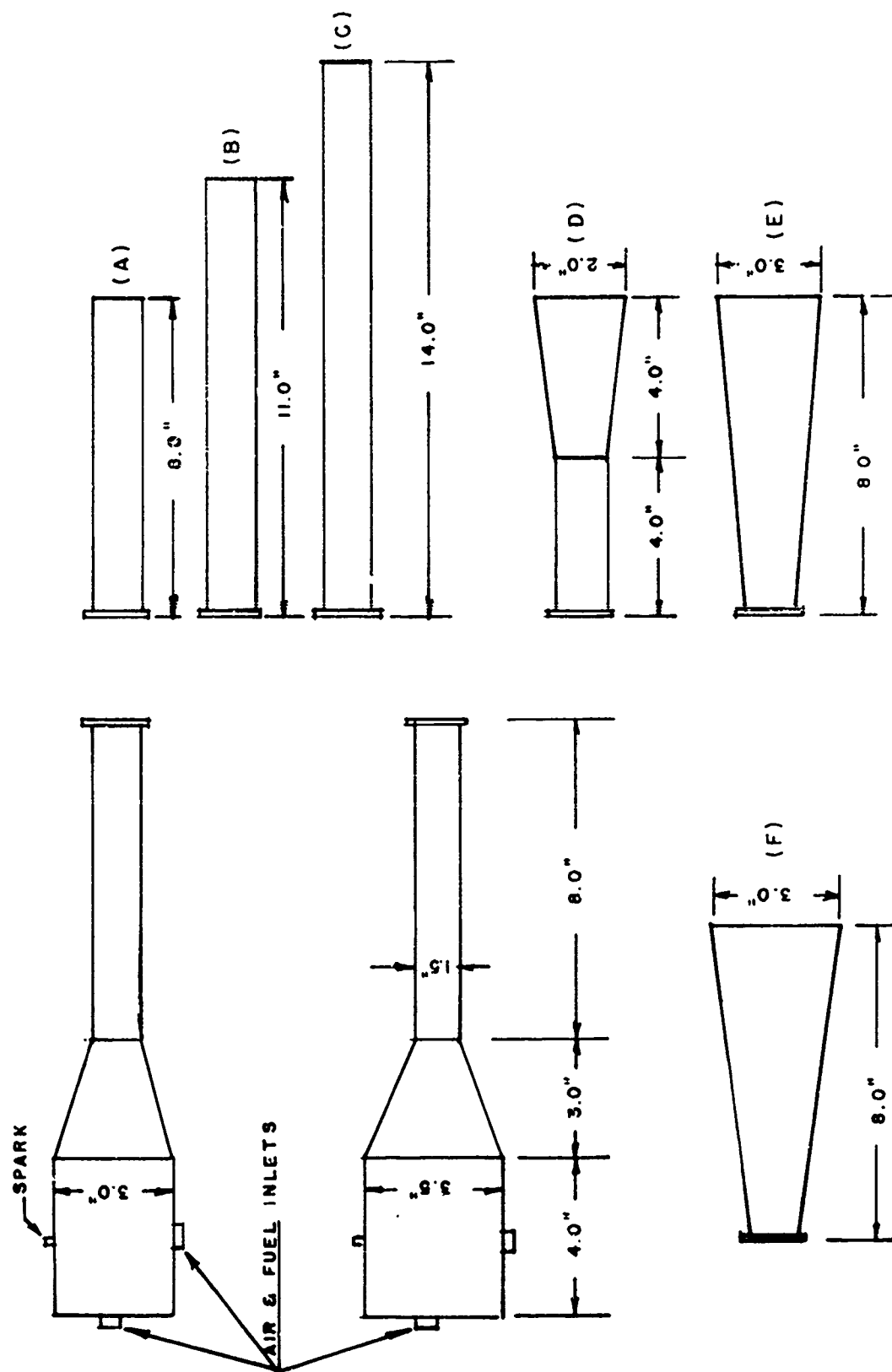


Fig. 1

DIAGRAM OF THRUST
MEASURING APPARATUS

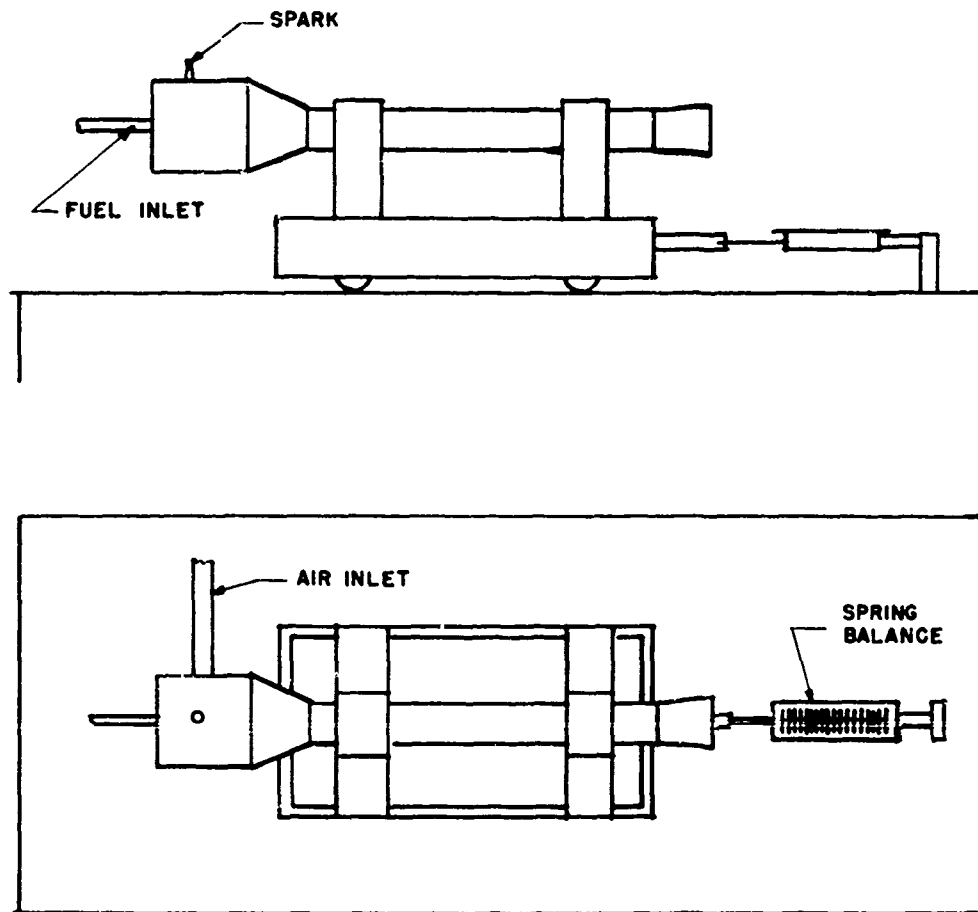


Fig. 2

VARIATION OF SPECIFIC IMPULSE WITH TAILPIPE LENGTH FUEL-PROPANE.

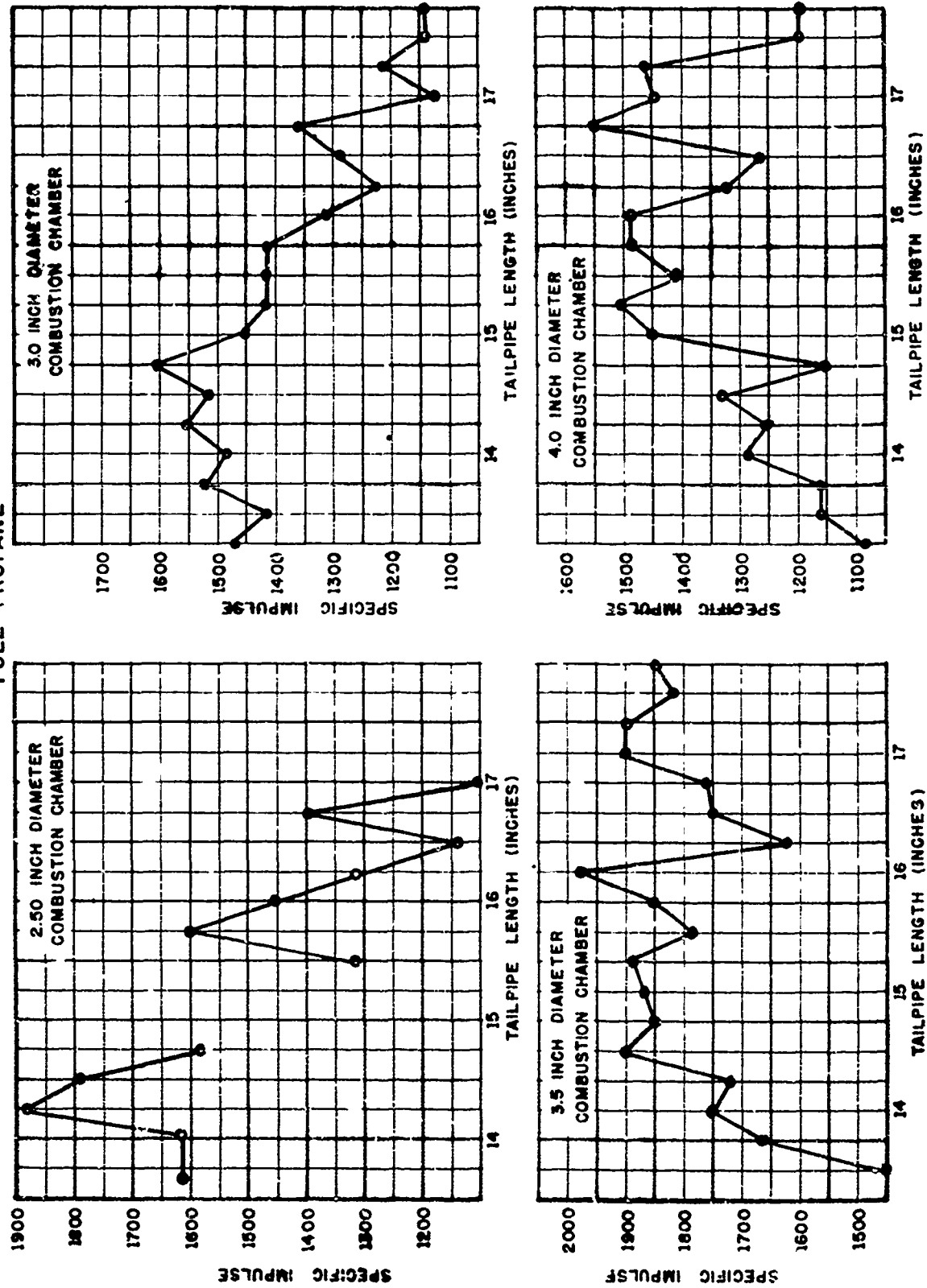


Fig. 3

VARIATION OF SPECIFIC IMPULSE WITH TAILPIPE LENGTH FUEL - METHANE

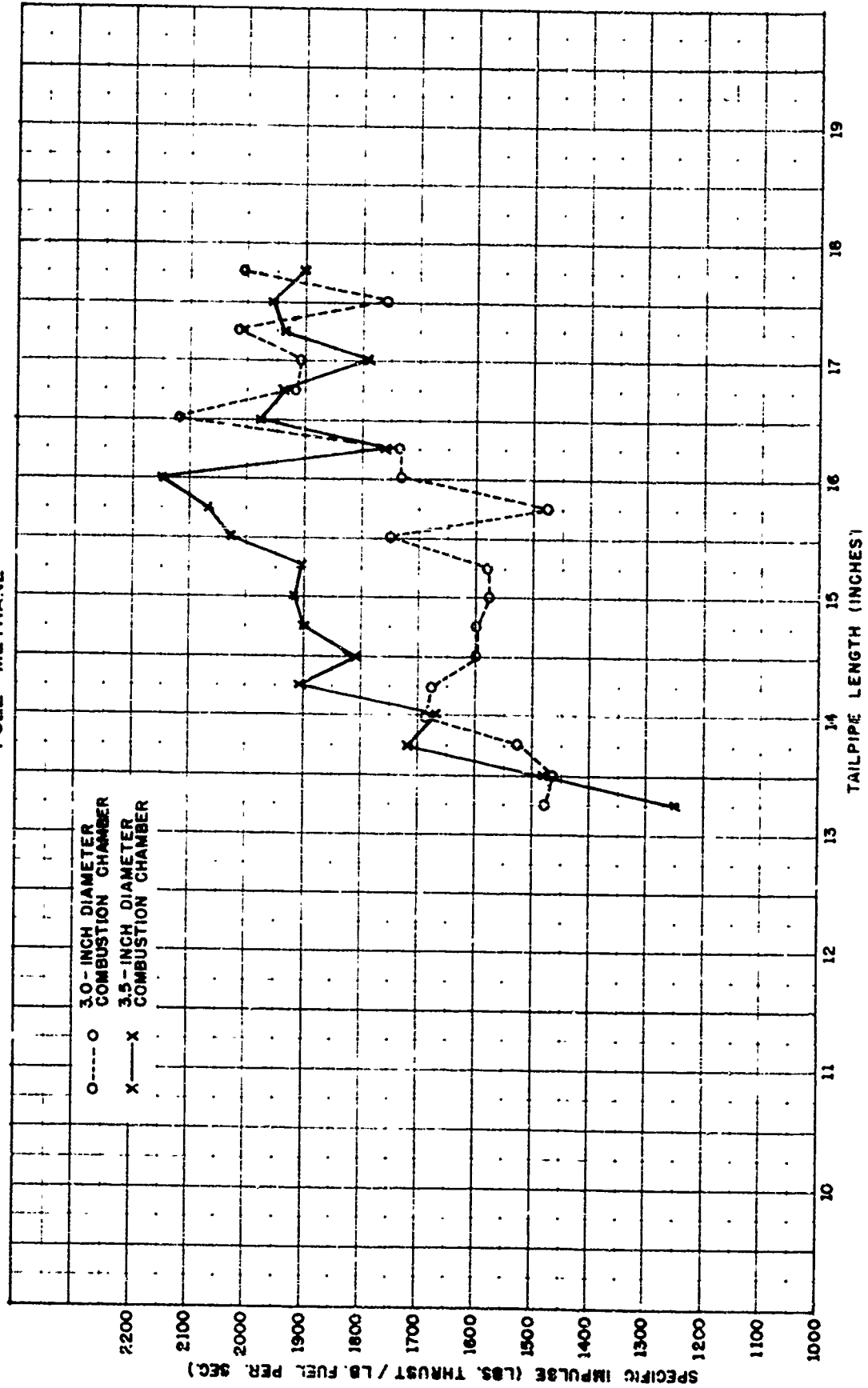


Fig. 4

VARIATION OF SPECIFIC IMPULSE WITH TAILPIPE LENGTH

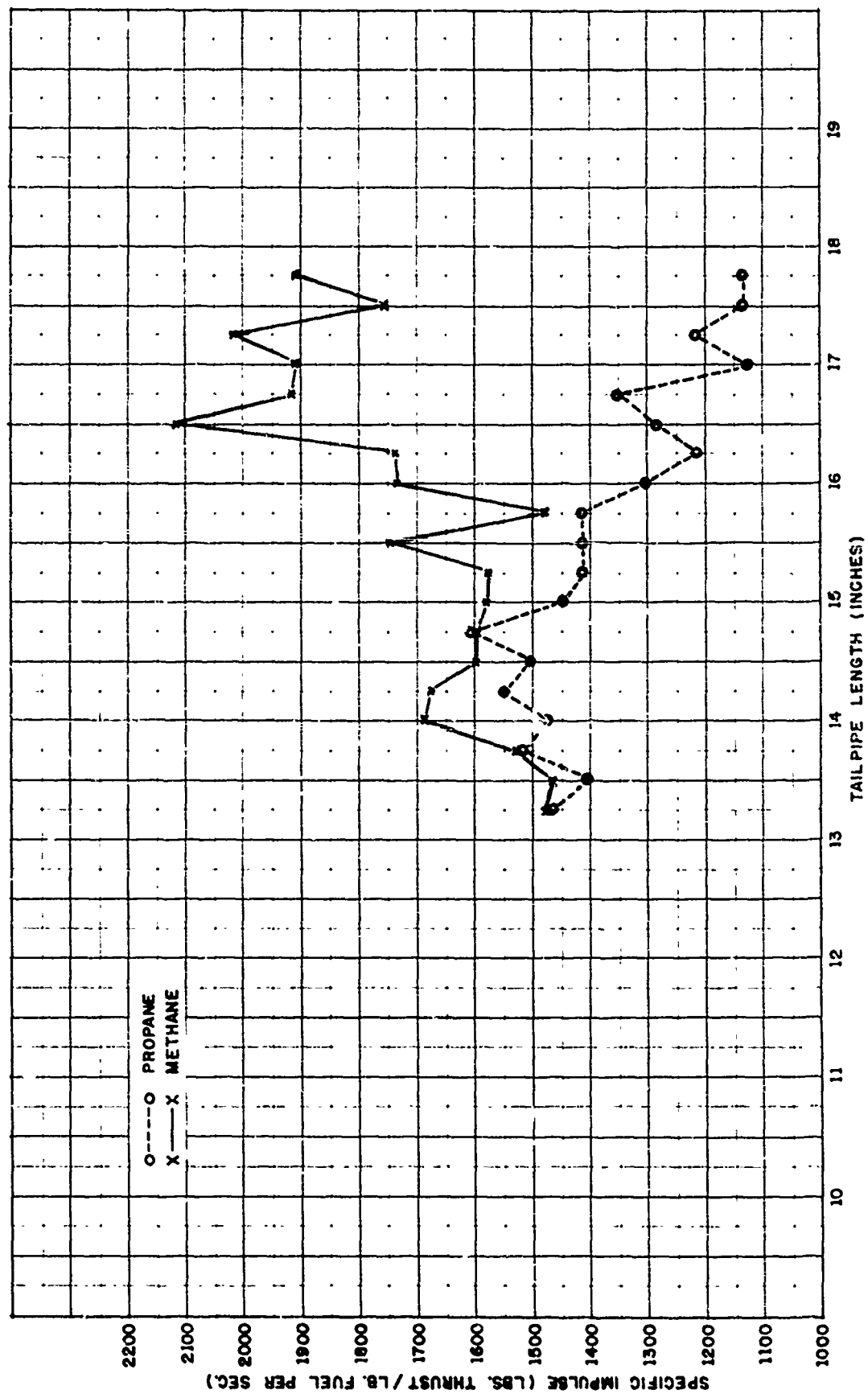


Fig. 5

VARIATION OF SPECIFIC IMPULSE WITH TAILPIPE LENGTH

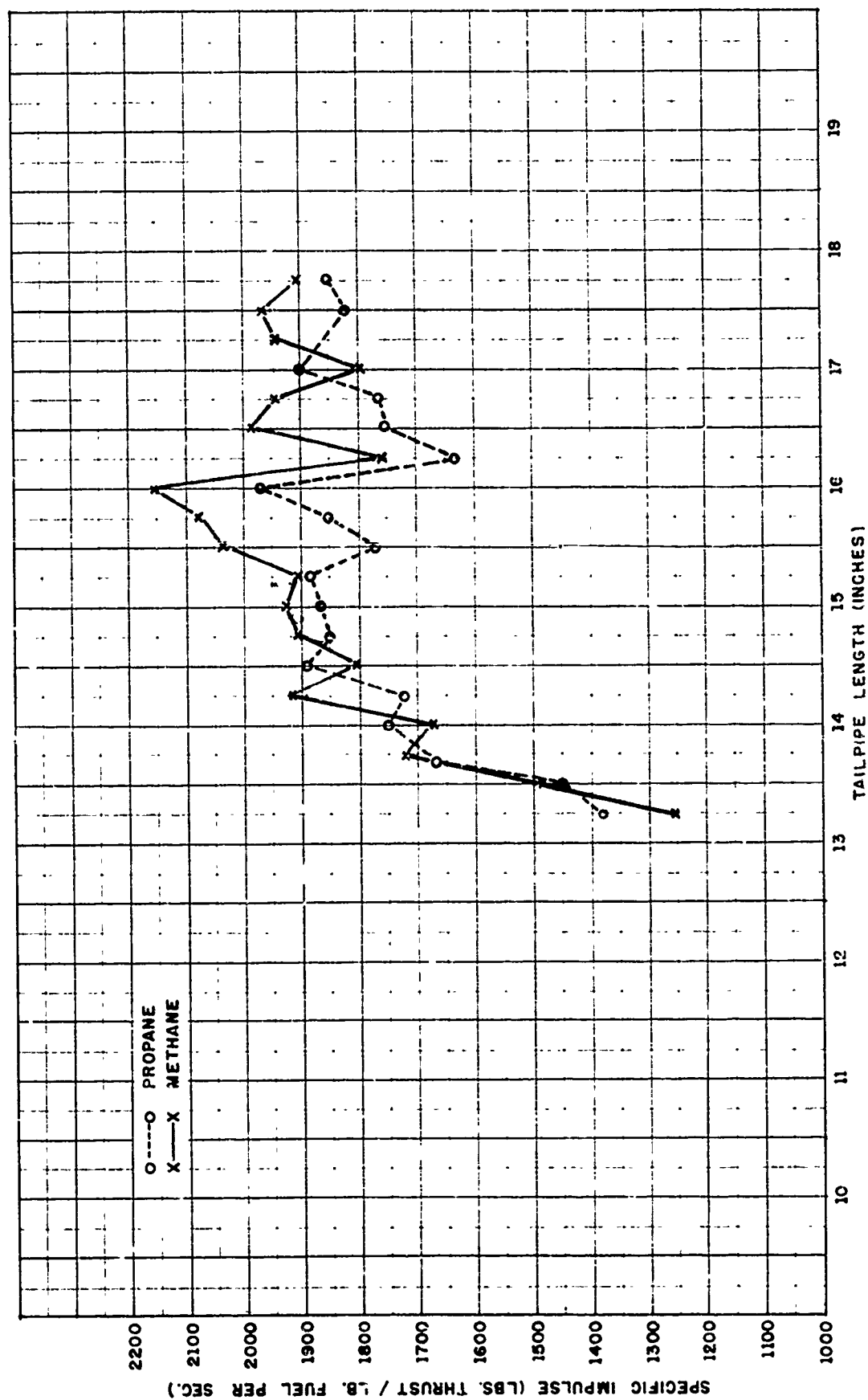


Fig. 6

AIR SPECIFIC IMPULSE vs AIR FUEL RATIO

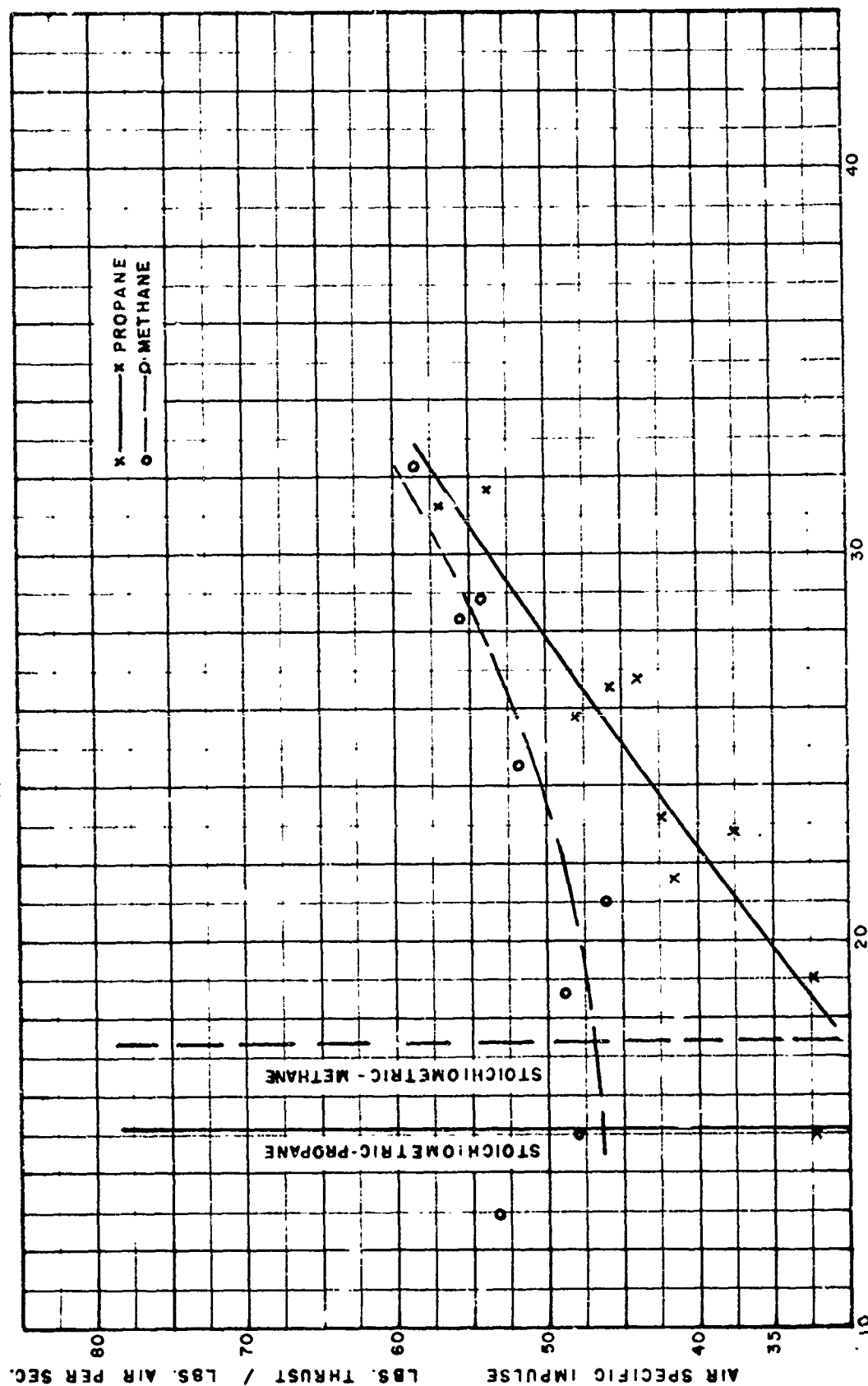


Fig. 7

PRESSURE VARIATION IN 4.0 INCH
DIAMETER COMBUSTION CHAMBER

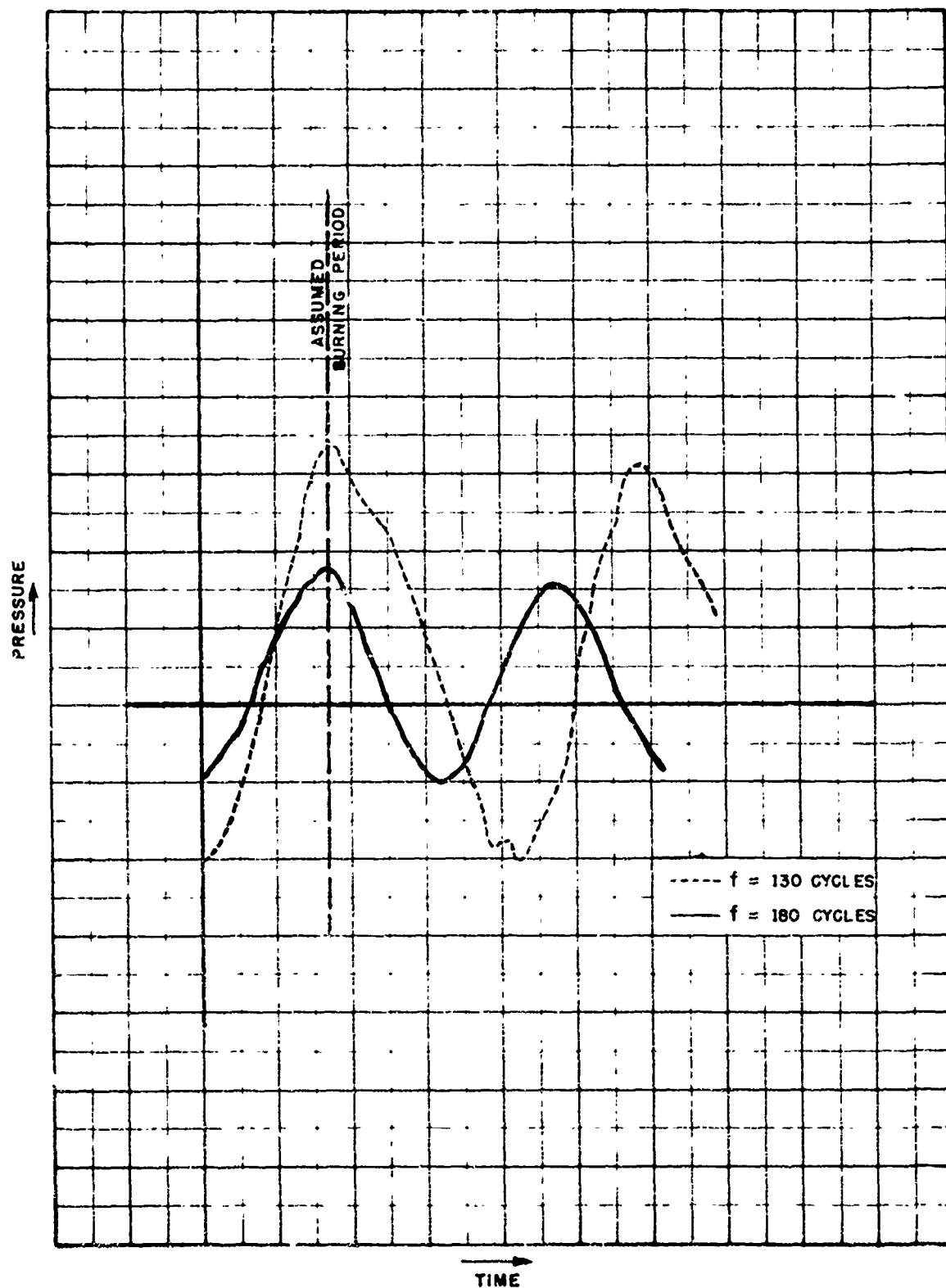
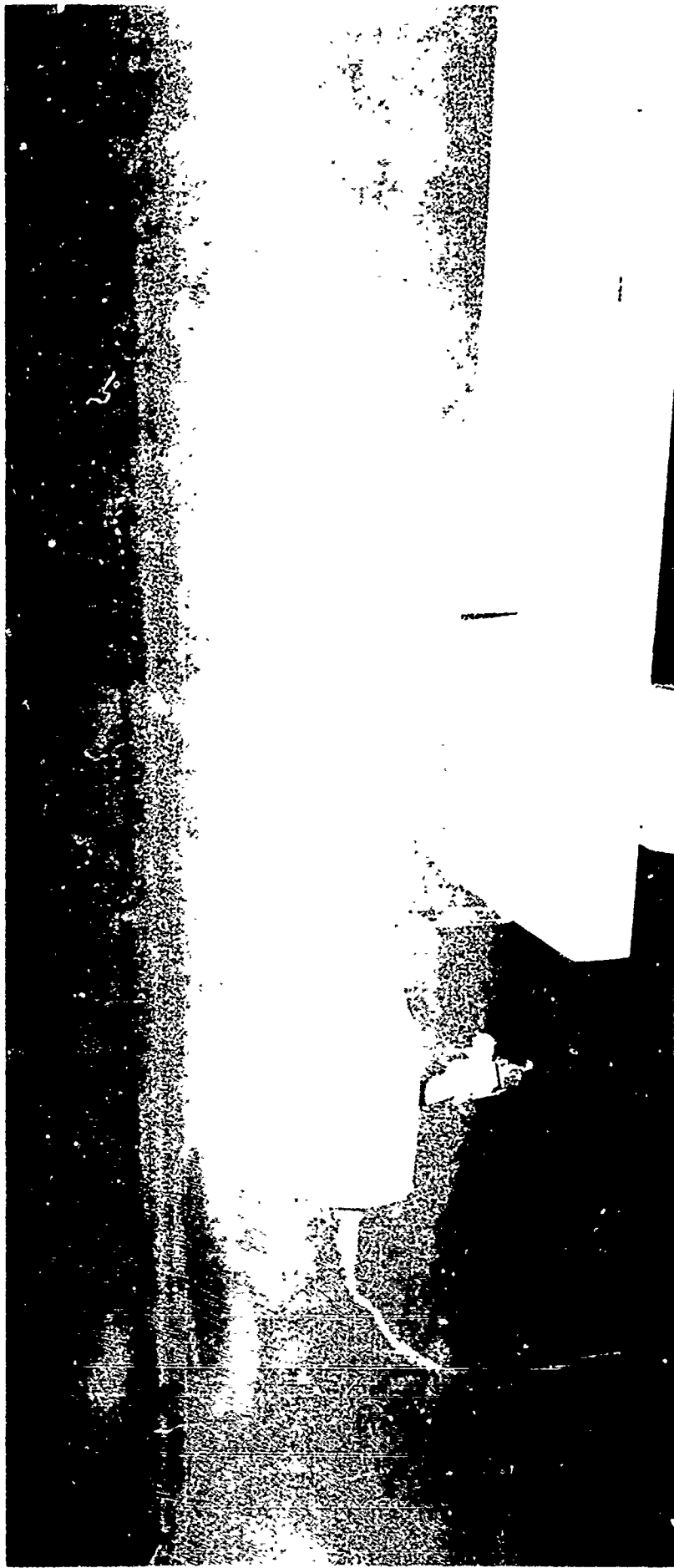
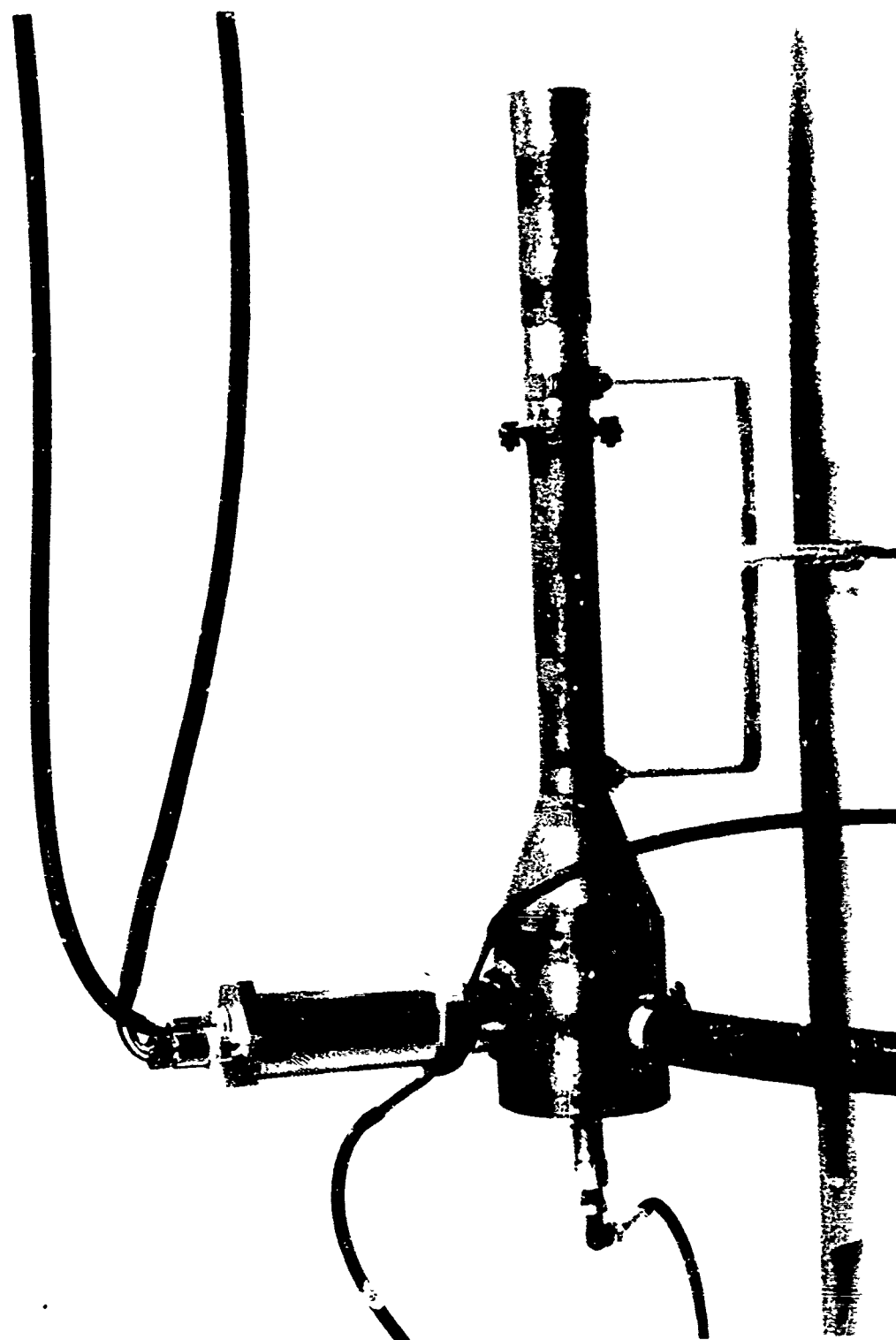


Fig. 8



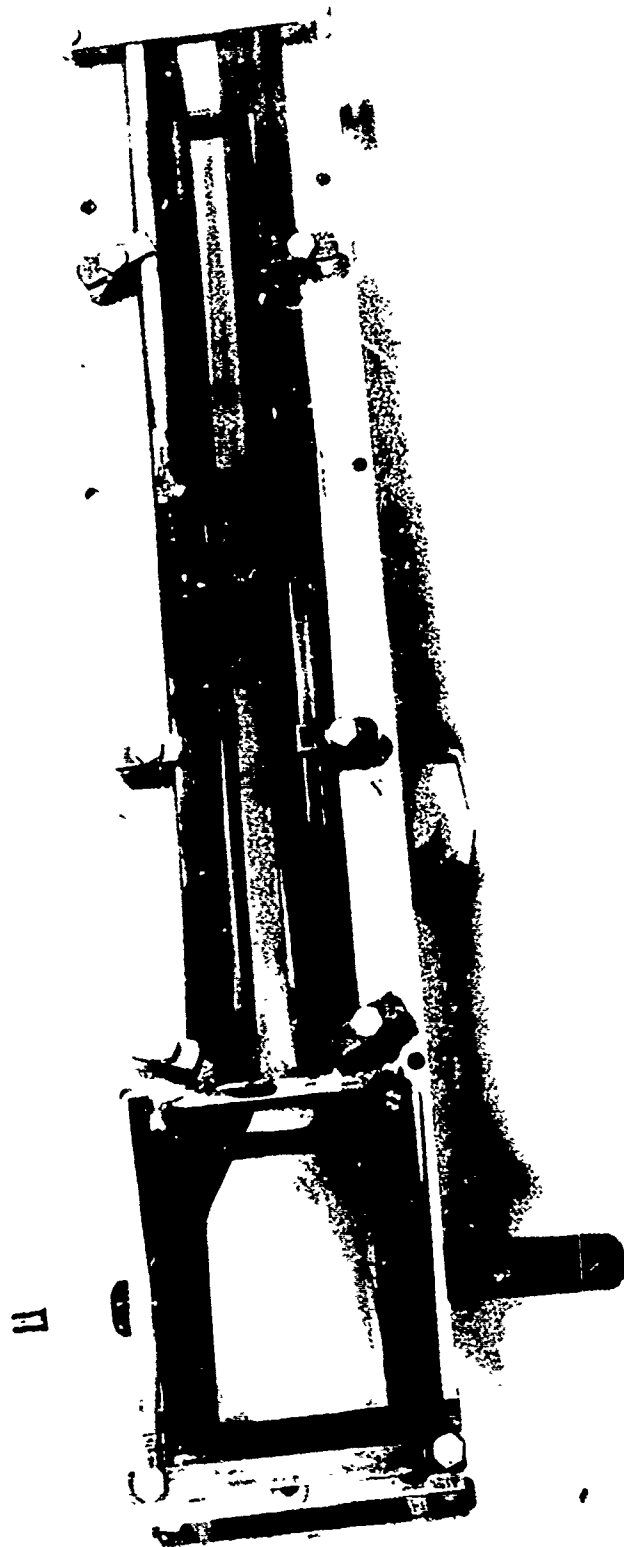
VALVELESS JET MODEL WITH 3.50 INCH DIAMETER COMBUSTION CHAMBER

Fig. 9



F.M. PRESSURE GAGE MOUNTED ON THE 4.0 INCH DIAMETER COMBUSTION CHAMBER

Fig. 10



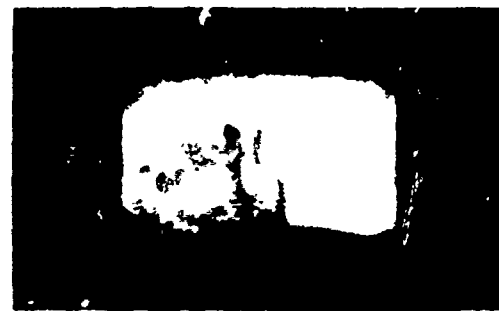
TWO-DIMENSIONAL MODEL OF THE VALVELESS JET

Fig. 11

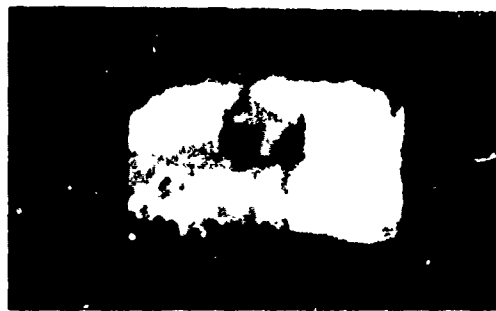
STAGES IN INTERMITTENT
AIR-FUEL INJECTION PROCESS



a



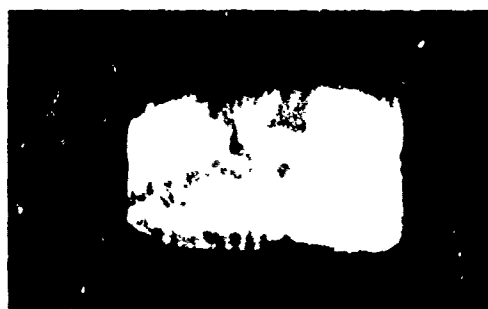
b



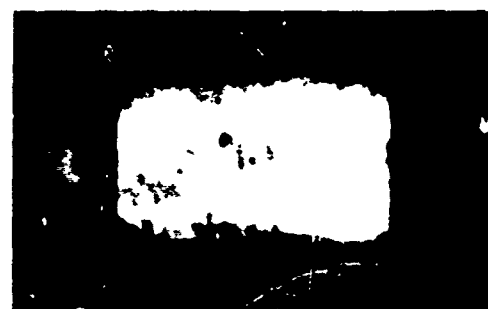
c



d



e



f

Fig. 12